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Hydrologic response of the Crow Wing Watershed, Minnesota, to mid-Holocene climate change

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Abstract

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Keywords

Paleohydrology, Climate chagne, Hydrogeology, Modeling, Paleolimnology

Disciplines

Atmospheric Sciences | Climate | Fresh Water Studies | Hydrology

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Hydrologic response of the Crow Wing Watershed, Minnesota, to mid-Holocene climate change

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ABSTRACT

In this study, we have integrated a suite of Holocene paleoclimatic proxies with mathematical modeling in an attempt to obtain a comprehensive picture of how watersheds respond to past climate change. A three-dimensional surface-water–groundwater model was developed to assess the effects of mid-Holocene climate change on water resources within the Crow Wing Watershed, Upper Mississippi Basin in north central Minnesota. The model was first calibrated to a 50 yr historical record of average annual surface-water discharge, monthly groundwater levels, and lake-level fluctuations. The model was able to reproduce reasonably well long-term historical records (1949–1999) of water-table and lake-level fluctuations across the watershed as well as stream discharge near the watershed outlet. The calibrated model was then used to reproduce paleogroundwater and lake levels using climate reconstructions based on pollen-transfer functions from Williams Lake just outside the watershed. Computed declines in mid-Holocene lake levels for two lakes at opposite ends of the watershed were between 6 and 18 m. Simulated streamflow near the outlet of the watershed decreased to 70% of modern average annual discharge after ~200 yr. The area covered by wetlands for the entire watershed was reduced by ~16%. The mid-Holocene hydrologic changes indicated by these model results and corroborated by several lake-core records across the Crow Wing Watershed may serve as a useful proxy of the hydrologic response to future warm, dry climatic forecasts (ca. 2050) made by some atmospheric general-circulation models for the glaciated Midwestern United States.

Keywords: paleohydrology, climate change, hydrogeology, modeling, paleolimnology.

INTRODUCTION

Although it has been known for some time that aquifer systems respond to changes in climate on time scales of decades to centuries (Sheehan, 1994; Heinl, 1996; Edmunds et al., 1999; Corbet, 2000), how these changes affect other aspects of the watershed hydrologic cycle has only recently been given serious consideration (Yeh and Eltahir, 1998; Levine and Salvucci, 1999; Kim et al., 1999; York et al., 2002; Cohen et al., 2006). If water-table aquifers are in good hydrologic connection to surface-water bodies, lake levels and stream discharge will be modified as groundwater levels fluctuate (e.g., Winter, 1983; Alley and Leake, 2004; Bredehoeft, 2002; Sophocleous, 2000; Kendy, 2003). Whereas general atmospheric circulation models have been used effectively to predict past (Cooperative Holocene Mapping Project [COHMAP], 1988) and future (Cubasch et al., 2001) changes in land-surface hydrologic conditions, global climate models (e.g., Atmospheric Global Climate Model [AGCM], by COHMAP members, 1988) use coarse spatial discretization (on the order of 10^4 km^2) and are not able to incorporate small-scale hydrological features such as streams, lakes, and aquifers, which makes it difficult for direct comparison of AGCM paleoclimatic reconstructions with those provided by lake-sediment cores. Forecasting future hydrologic changes has considerable uncertainty because of the wide variability in precipitation produced by different atmospheric models (Cubasch et al., 2001).

Recently, distributed-parameter hydrologic models have proven effective in reconstructing past hydrologic conditions in relatively small glaciated watersheds (e.g., >10 km^2) at a

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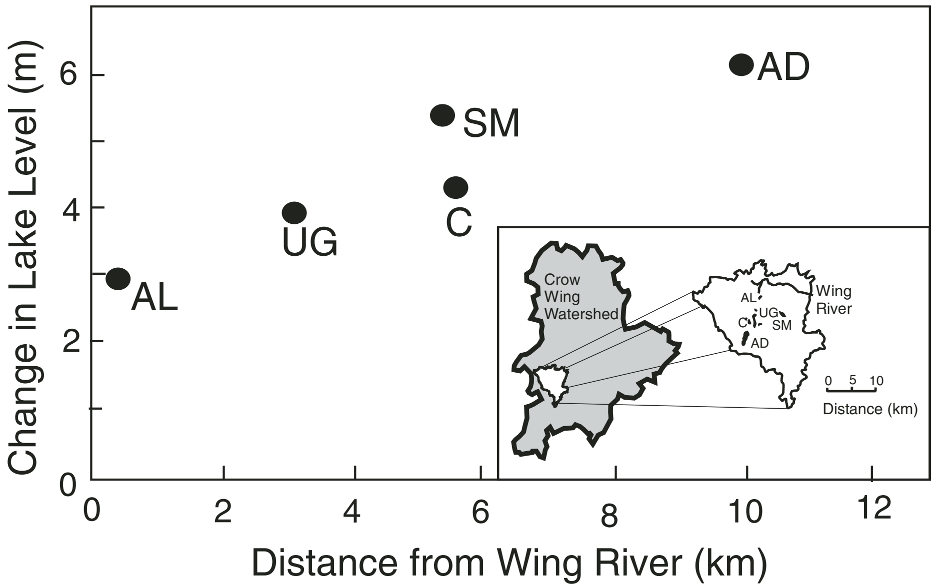

Figure 1. Inferred decline in lake level during mid-Holocene (present day minus mid-Holocene) vs. distance from the Wing River for five lakes within the Parkers Prairie Watershed (after Almendinger, 1993, and Digerfeldt et al., 1992). AL—Almora Lake, UG—Upper Graven Lake, C—Cora Lake, SM—South Maple Lake, AD—Lake Adley.

horizontal spatial grid resolution down to 100 × 100 m (Filby et al., 2002; Donovan et al., 2002). The advantage of using a "hindcasting" approach to assess the impact of past climate change on water resources is that a suite of paleoclimatic proxy records often exists that provides ground truth to constrain the effort. To date, previous studies have not integrated all aspects of the surface hydrologic cycle. Here we present a new watershed-scale mathematical model that represents changes in streamflow, soil moisture, wetlands extent, groundwater, and lake-level fluctuations in a single analysis. We believe our approach gives a near-complete assessment of a watershed's potential response to climate change. We applied this model to the Crow Wing Watershed within the Upper Mississippi Basin. Prior paleolimnologic studies carried out within the west-central part of this watershed (Digerfeldt et al., 1992; Almendinger, 1993) suggested that lake levels fell between 2.9 m and 6 m during the Mid-Holocene Warm Period between 3500 and 7700 ^{14}C yr B.P. (Fig. 1). Interestingly, Digerfeldt et al. (1992) found an empirical relationship between the magnitude of lake-level decline and the distance from the lake to the Parkers Prairie Watershed outlet. Almendinger (1993) subsequently demonstrated that this behavior could be explained by groundwater hydrodynamics.

In the remainder of this paper, we describe the geologic and hydrologic conditions within the Crow Wing Watershed. Lake-sediment cores collected along transects in two lakes (Lake Mina and Moody Lake) at opposite ends of the watershed are described and interpreted. These same lakes were instrumented with pressure transducers to correlate seasonal groundwater and lake-level fluctuations. We then describe a three-dimensional hydrologic model of this watershed that is used to predict changes in lake levels, stream discharge, and water-table fluctuations. The model was first calibrated with a 50 yr record of lake-level and water-table fluctuations as well as mean monthly stream discharge of the Crow Wing River near the outlet of the watershed. The calibrated model was then used to reconstruct mid-Holocene hydrologic conditions across the watershed.

STUDY AREA

Quaternary Geology and Morphology

The Crow Wing Watershed is a relatively large (1.4×10^4 km^2) geographic feature that was formed by multiple episodes of Pleistocene glacial and interglacial cycles. It hosts numerous wetlands, lakes, and streams (Fig. 2). Late Wisconsinan glaciation was most influential in forming the present physiography. The Crow Wing Watershed is bounded by three prominent late Wisconsinan moraines (Harris and Knaeble, 1999; Fig. 3). To the east is the St. Croix moraine of the Rainy and Superior lobes, composed of younger drift from northeastern Minnesota and the Lake Superior Basin, and to the west and south is the arcuate Alexandria moraine complex, which consists of sandy calcareous drift of the Wadena lobe, overlain locally by silty calcareous drift of the Des Moines lobe (Fig. 3). On the north is the Itasca moraine, formed during a secondary advance of the Wadena lobe. The moraines are dotted with lakes of all dimensions, most of ice-block origin. Lakes within the watershed are characterized by a wide range in depth (2–30 m). The Wadena drumlin field is a region of low relief and strong lineation and is covered by outwash deposits that are thickest in the swales between drumlins and thinnest where they overlie buried drumlins (Wright and Ruhe, 1965; Harris and Knaeble, 1999; Lindgren, 2002; Fig. 3). The drumlin field contains few lakes but numerous scattered wetlands (Leverett, 1932) (Fig. 2). Glacial deposits range in thickness from 30 to 100 m (Lindholm et al., 1972). The tills are highly heterogeneous, making it difficult to assign hydrostratigraphic properties to individual layers of drift.

Modern Climate

The Crow Wing Watershed is an excellent venue for studying the impact of climate change on surface and subsurface hydrology. The watershed lies in a climatic transition zone where air masses from the Arctic, the Pacific Ocean, and the Gulf of Mexico interact (Bryson, 1966; Bryson and Hare, 1974; Harvey and Welker, 2000). Average annual monthly temperatures within the watershed range between −13 and +18 °C. Storm systems coming from the west draw moisture from the Gulf of Mexico and are by far the main source of precipitation. Between 65% and 75% of the annual precipitation occurs in the May–September growing season (Baker et al., 1979). In the Crow Wing Watershed, ~75% of the annual precipitation (~70 cm) is returned to the atmosphere by evapotranspiration (Baker et al., 1979). About 13 cm/yr (18%) of precipitation becomes recharge to surficial unconfined aquifers (Helgesen, 1977; Lindholm, 1970; Lindgren, 2002). There are only modest spatial gradients in precipitation and runoff across the watershed.

Minnesota's Holocene Climatic History

Lake sediment records indicate that the mid-Holocene in Minnesota and adjacent areas witnessed an increase in aridity and temperature (COHMAP members, 1988). This is based on multiple climatic proxies such as sedimentological, geochemical, and isotopic records as well as pollen and other microfossils (Bartlein et al., 1984; Dean et al., 1984; Dean and Schwalb, 2000; Smith et al., 2002), lake-level fluctuations (Almendinger, 1993; Yu, 1997;

Filby et al., 2002), and dune activity (Forman et al., 2001). Locke (1995) used pollen-transfer functions of Whitlock et al. (1993) and pollen data from Williams Lake sediment cores from the Shingobee Watershed (Fig. 4) to infer mid-Holocene mean monthly climate. Inferred temperatures for January and July increased by 3.5 and 4 °C, respectively, compared to today. Mean annual precipitation decreased by 25 cm relative to modern conditions. This Mid-Holocene Warm Period is believed to have extended from ca. 3500 to 7700 yr B.P.

The prairie-forest border shifted eastward >100 km in the mid-Holocene before returning to its present location (Webb et al., 1983), indicating a prolonged period of warmer, drier climate. This period coincides with changes in the amount of summer insolation as determined by Earth-Sun orbital relations (Yu and Ito, 1999), modified in the early Holocene by the effects of the retreating Laurentide ice sheet on the atmospheric circulation patterns. Coincident with the shift in the prairie-forest border was the lowering of lake levels. This phenomenon was first inferred from the alteration of macrofossils of wetland plants and aquatic plants at the Kirchner Marsh area for the time of prairie expansion (Watts and Winter, 1966) and from pollen evidence for vegetation change in the Itasca area of north-central Minnesota (McAndrews, 1966).

Hydrologic Setting

The Crow Wing Watershed contains >175 lakes and hundreds of wetlands covering ~8.5% and 5.6% of the watershed, respectively (Fig. 2). Some areas of the watershed are hydrologically closed, whereas others are drained by a series of streams. Evapotranspiration is the only process controlling discharge from undrained regions of the watershed. The Crow Wing Watershed can be divided into the Crow Wing, Long Prairie, and Red Eye River subwatersheds. Flow along the main stem of the Crow Wing River is stable because of the regulating effect of lakes and wetlands at medium to high flows and the sustaining effect of groundwater discharge (base flow) from outwash areas during low-flow periods (Lindgren, 2002). Average streamflow for the Crow Wing River at its confluence with the Mississippi River is ~28 m^3/s^{-1} (~1000 cfs; Lindholm et al., 1972). The average annual streamflow fluctuated less than one order of magnitude during the period of record between 1940 and 2000.

Typical of young glacial terrain, the area is characterized by hummocky topography, including many undrained depressions that contain lakes and wetlands. The area is relatively flat, and depth to the water table is <3 m over

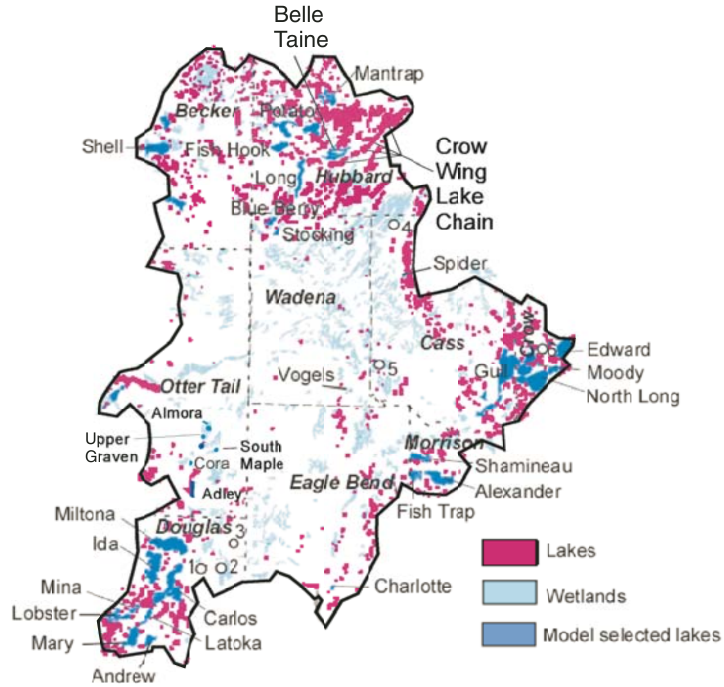

Figure 2. Lakes and wetlands in the Crow Wing Watershed in north-central Minnesota. County names are in italics. Selected lakes (dark blue) and wells (circles with numbers) discussed in this study are also shown.

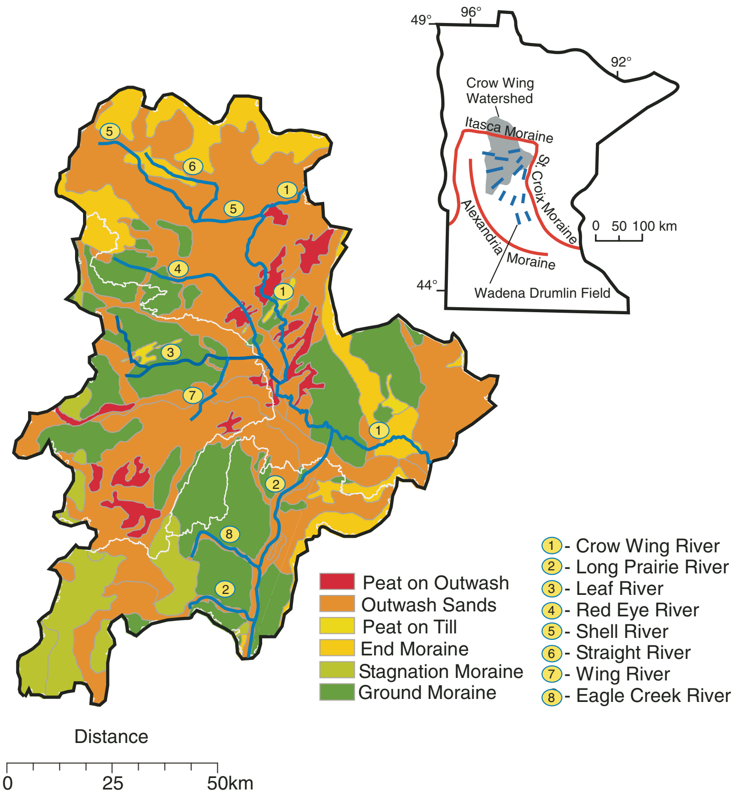

Figure 3. Quaternary geologic map of the Crow Wing Watershed, depicting distribution of low (end moraine, stagnation moraine, and ground moraine) and high (outwash sands) permeability deposits. The position of the Crow Wing Watershed with respect to the Itasca, St. Croix, and Alexandria moraines and the Wadena drumlin field is shown in the inset (from Mooers and Norton, 1997). Major streams and rivers of the Crow Wing Watershed are also shown.

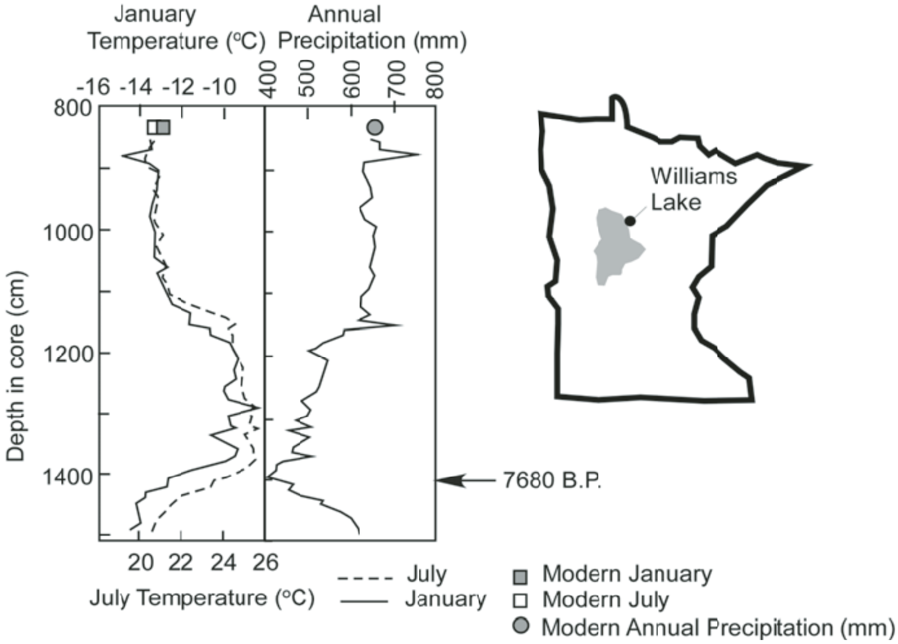

Figure 4. Reconstructed Holocene climate from Williams Lake, based on pollen transfer functions (after Locke, 1995).

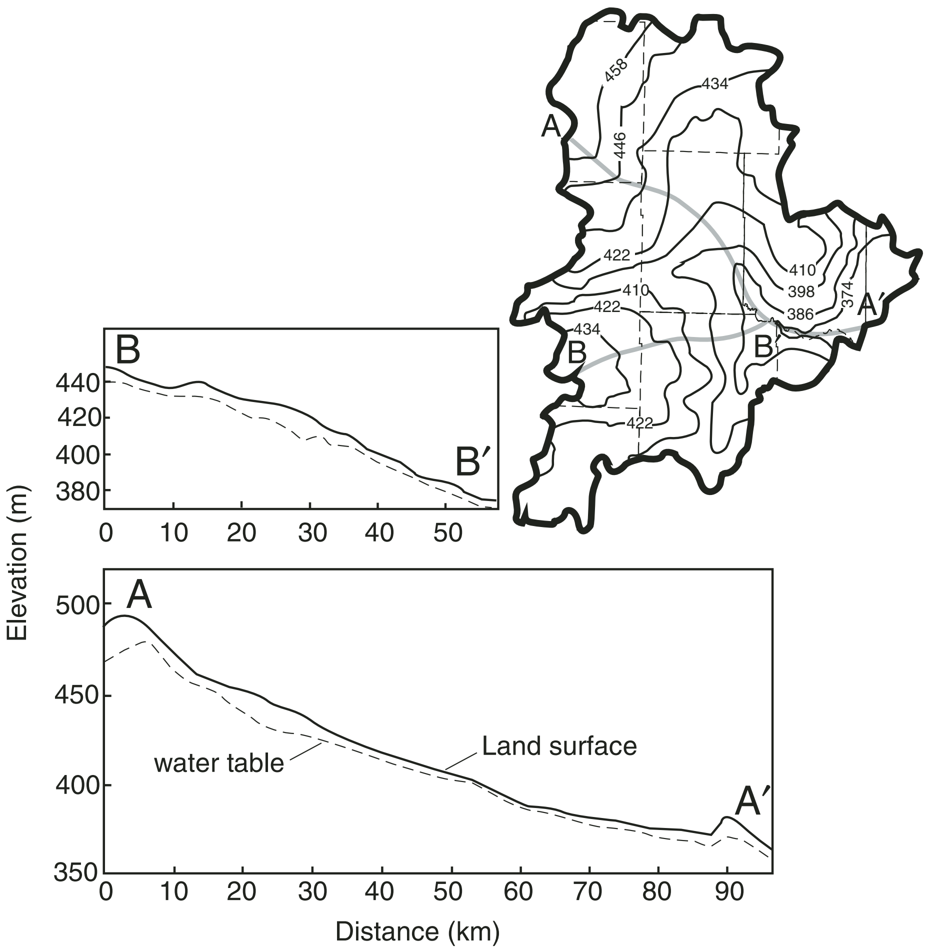

Figure 5. Water-table map and cross sections across the Crow Wing Watershed (from Cohen et al., 2006).

~30% of the area. The water table varies across the watershed by ~140 m (340–480 m above mean sea level; Fig. 5). The regional water table presented in Figure 5 is based on a calibrated, steady-state, free-surface groundwater-flow model (MWT3D) described by Corbet and Knupp (1996) and Cohen et al. (2006). As part of the model calibration exercise, 3037 water-table-elevation measurements reported by the U.S. Geological Survey (http://nwis.waterdata.usgs.gov/mn/nwis/gwlevels) from wells drilled across the Crow Wing Watershed were used. The model was calibrated to the observed water-level data by inverse methods (PEST; Watermark Numerical Computing, 2001). The average residual (computed minus observed water levels) was 1.3 m.

Historical lake and water-table records across the watershed indicate that the magnitude and response time of water-table fluctuations are sensitive to the position within the watershed. The largest annual water-table and lake-level fluctuations (2–3 m) occur in the upland parts of the watershed. Fluctuations within the low-lying regions of the watershed have higher frequency and smaller amplitude (<1 m). High-frequency fluctuations in low-lying regions are probably due to rapid infiltration through thin unsaturated zones in the lowlands (Cohen et al., 2006). Plots of temporal water-table and lake-level elevations are presented and discussed in the Results section.

FIELD METHODS

Field work was carried out between 2000 and 2004 to assess modern and paleo-groundwater and lake-level fluctuations across the Crow Wing Watershed. To assess interactions between modern water-table and lake-level fluctuations, wells were drilled in July 2000 at two lakes near Alexandria (Lake Mina) and Brainerd (Moody Lake) (Fig. 2). These lakes were subsequently cored to ascertain changes in lake levels during the Mid-Holocene Warm Period. The positions of these study sites complement existing sites studied by Almendinger (1993) in the center of the watershed. The drilling was carried out with a 6-in.-diameter auger rig operated by the U.S. Geological Survey. Water-table-monitoring wells were installed down gradient from each lake. The wells were constructed of 5.1-cm-diameter PVC casing with a 1.6 m section of slotted screen at the bottom of the well. The wells were installed at a depth ~2 m below the water table at each site (7.3 and 8.8 m below the land surface). The screened interval was backfilled with sand and then grouted with bentonite up to the land surface. Sediments encountered during well installations were primarily medium-grained sand near Moody Lake and clay-rich till near Lake Mina.

The hydraulic head and the lake stage were monitored continuously during 2002–2003 with Druck 100 kPa pressure transducers, which were connected to Campbell Scientific data loggers programmed to record water levels four times daily (Fig. 6). Breaks in the data record were caused by equipment malfunction. Groundwater and lake-level data are well correlated on a seasonal scale, suggesting a good hydrologic connection between the phreatic aquifer and the lakes. Large daily fluctuations in the well data during summer months are due to the effects of daytime evapotranspiration. Daily fluctuations in lake levels are caused by waves and/or lake seiche.

Mid-Holocene changes in lake levels across the Crow Wing Watershed are inferred in this study through analysis of buried shore sediments contained within the cores of Lake Mina and Moody Lake. Two transects from shallow to deeper water were cored in the winters of 2001 and 2002 at Moody Lake and Lake Mina, respectively. Buried sand layers were encountered in both transects. All cores at Mina and Moody Lakes were taken with a square-rod piston corer (Wright, 1991). The cores were analyzed for grain size and total carbon.

The sand layers encountered at Lake Mina (Fig. 7) and Moody Lake (Fig. 8) are interpreted as shore deposits at times of low lake levels that were subsequently buried by deeper-water facies (e.g., gyttja) when lake levels rose. The pollen stratigraphy indicates that the sand layers were formed during the Mid-Holocene Warm Period. Eolian deposition is unlikely as an alternate explanation because of the difficulty in transporting sand across the lake in the summer, or across the ice in the winter. Deposition from strong runoff events was rejected, because the lakes have no inlet streams. These data indicate that mid-Holocene lake levels in low-lying parts of the watershed declined by only ~4.5 m (Fig. 7), while the surface of the lake, situated near the watershed divide, declined by as much as 14.7 m (Fig. 8). Near the shore of a lake, the sediments are dominated by sand, because wave action removes finer sediment, which is deposited in deeper water. When lake level lowers, the sand facies moves away from the former shore and buries fine sediment that had been deposited previously. At the same time, the sediment exposed by the lower lake level is subject to erosion and may be removed. When lake level rises again, fine sediment will be deposited on the eroded surface, making an unconformity. Thus at Moody Lake, core C from the lake center contains no sand at all, but in core A the buried multiple sand layers, underlain and overlain by fine organic sediment, represent an interval of fluctuating low lake level; and the pollen profiles for that core indicate that these processes were occurring during the first part of reforestation near the end of the prairie period. Buried sand layers are absent in core E, collected in still shallower water, implying that the initial fall and the last rise of the lake level were too rapid to record the migration of the sand facies toward and away from the lake center. Sand occurs at the base of core E, but pollen analysis indicates that it dates from the spruce zone, which is late-glacial. A core taken later from about the same spot as core E (core K) has a longer pollen record and shows that the Mid-Holocene Warm Period is completely missing from the geologic record, indicating an unconformity between the late-glacial and the late Holocene. At this time the lake level was low and much of the exposed sediment at sites E and K was removed by erosion, if it had ever been deposited there.

MATHEMATICAL MODEL

A three-dimensional hydrologic model of the watershed was constructed to determine the relationship between historical and mid-Holocene lake-level fluctuations and groundwater

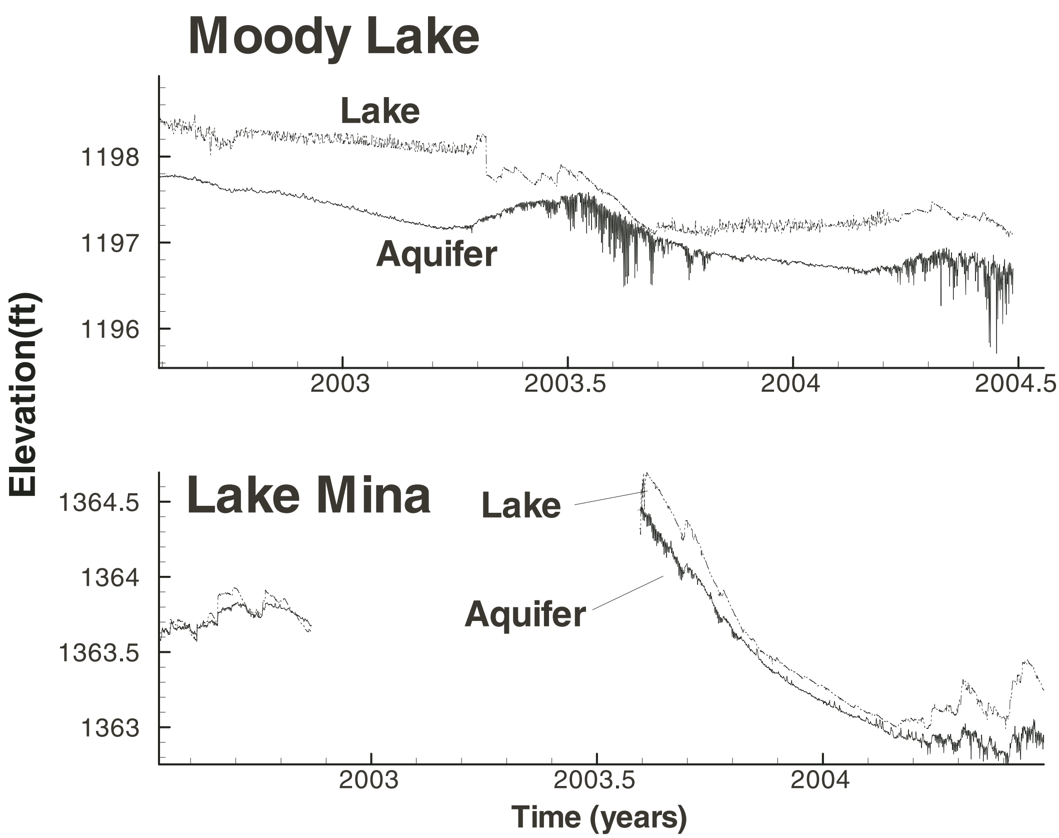

Figure 6. Comparison of lake and groundwater-table fluctuations for Lake Mina (Loken well) and Moody (South Moody well) recorded 12 July 2002. The locations of these wells are shown in Figure 7 (Moody Lake) and Figure 8 (Lake Mina).

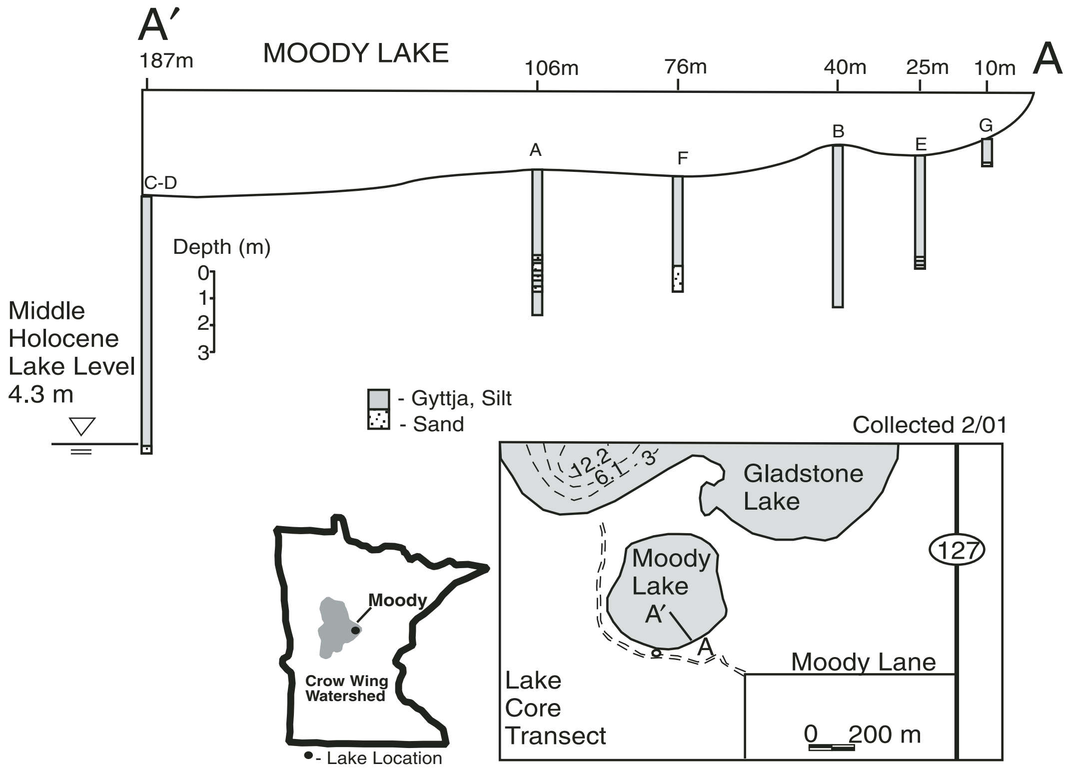

Figure 7. Inferred mid-Holocene paleolake levels from position of buried strandline from Lake Moody. The position of the lake core transect is indicated by the line A–A′. The small circle indicates the monitoring well, which was monitored for water-table fluctuations as part of this study.

hydrodynamics (see Appendix for details).[1] An important requirement of mid-Holocene hydrologic models is the need to represent dynamic surface-water and groundwater interactions in which lake levels and stream discharge are modified by local water-table conditions. The Crow Wing model represents major components of the land surface and subsurface (unconfined) hydrologic cycle, including runoff, evapotranspiration, infiltration, streamflow, lake-level fluctuations, and groundwater hydrodynamics. The model was necessarily simple because of the large length and time scales over which the model was applied. For example, monthly time steps were used that precluded representation of unsaturated-flow dynamics or event-based surface-water-runoff processes. Even if the requisite modern and paleoclimatic forcing were available on daily or shorter time intervals to permit representation of event-based hydrology, computational limitations would have precluded this implementation (Cohen et al., 2006).

The groundwater-flow equation (see Appendix A1; footnote 1) was solved by the finite element method. A structured grid used to represent the Crow Wing Watershed is composed of a series of 7278 nodal columns that constitute the triangulated land-surface mesh (Fig. 9). This results in a three-dimensional grid composed of 72,780 nodes and 422,880 tetrahedral elements. The land-surface expression of this mesh is a triangular grid that was used to represent the land-surface hydrology of the watershed (see Appendix A2–A6; footnote 1). In addition, the mesh was refined in areas near surface-water bodies and contacts between different till units while preserving a coarse-node spacing in other regions. The mesh was constructed to honor the surface-water drainage features (i.e., perennial streams) as well as major lithologic boundaries. The elevation of the land surface was derived from a 100 m digital elevation model (DEM) of the Crow Wing Watershed. Material parameters, including surficial geology, lake-node identifier, and lake bathymetry, were assigned to each surface element and node. The thickness of the aquifer unit ranged from ~100 m toward the northwestern and southern uplands to ~35 m at the discharge area toward the eastern boundary of the watershed (Lindholm, 1970). Glacial deposits within the Crow Wing Watershed are heterogeneous (Fig. 3). A single layer based on the Quaternary geologic map (Fig. 3) was used to assign aquifer properties. Lakes were represented as a surficial layer with higher hydraulic conductivity (three orders of magnitude higher than other surficial aquifers) and unit storage coefficient (Lee, 1996; Swain et al., 1996; Merritt, 1997). The bathymetry of the lakes was used to delineate the bottom of the high-conductance zone. This permitted the model to account for the changes in lake volume with depth. The model extended down to the top of a basal till unit of pre-Wisconsinan age. The lakes that were cored as part of this study (Lake Mina and Moody Lake) were discretized at a much finer resolution (50–100 m) than the rest of the watershed (500–1000 m). The grid was vertically discretized into 10 horizontal layers that represented the 35–100-m-thick surficial (unconfined) aquifer in the Crow Wing Watershed.

[1]GSA Data Repository item 2007045, Appendix, is available on the Web at http://www.geosociety.org/pubs/ft2007.htm. Requests may also be sent to editing@geosociety.org.

Climatological Data

Climatological data used were taken from a climate data set that includes monthly mean temperature and precipitation for 50 calendar years (1949–1999) recorded at 119 monitoring stations within and adjacent to the watershed (source: Minnesota Climatology Working Group Web site: http://climate.umn.edu). The climatic data were interpolated onto adjacent surface nodes with an inverse distance method (Zimmerman et al., 1999).

Soil and Vegetation Data

Soil-zone parameters required to compute evapotranspiration (ET), runoff (R), and infiltration (I) included field capacity (h_{fc}), saturation porosity (h_{ϕ}), wilting point (h_w), and thickness

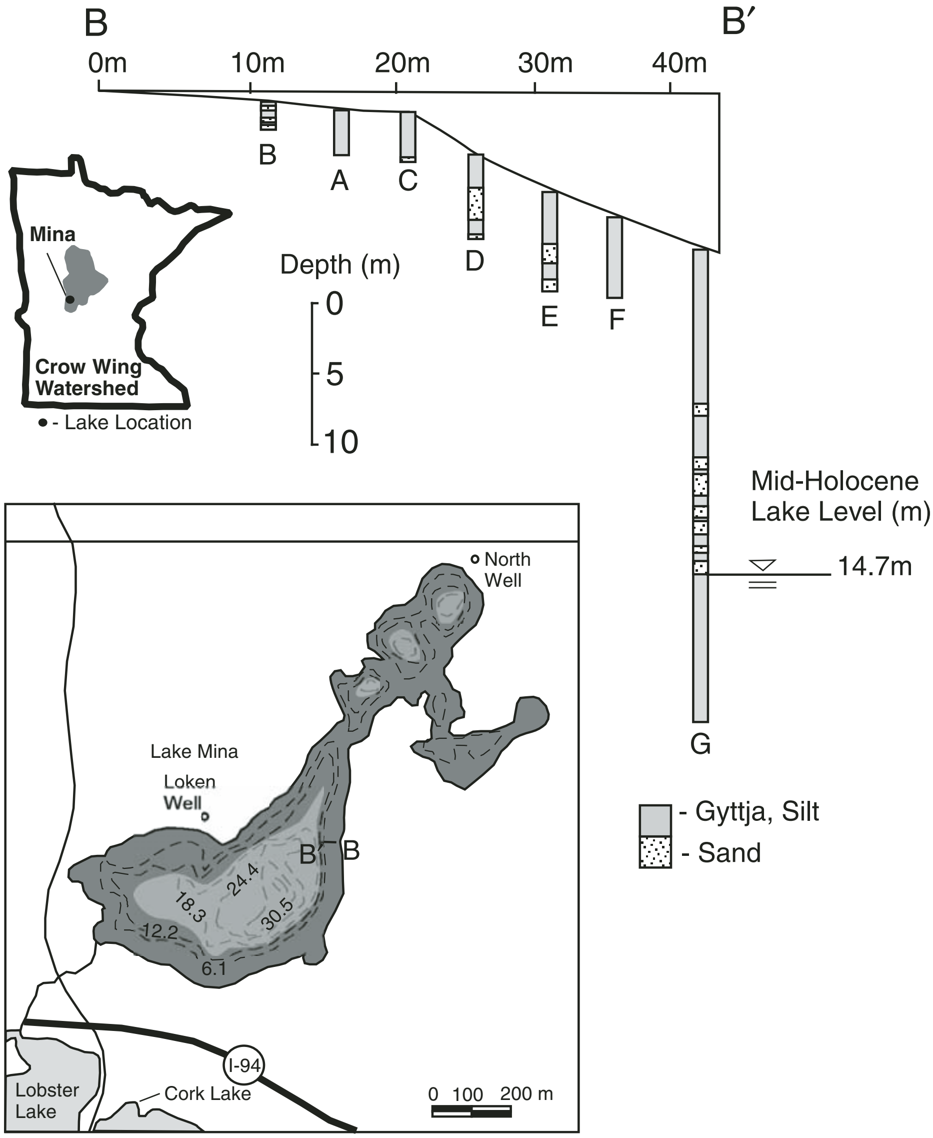

Figure 8. Inferred mid-Holocene paleolake levels from position of buried strandline from Lake Mina. The position of the lake core transect is indicated by the line B–B′. The small circle indicates the monitoring well, which was monitored for water-table fluctuations as part of this study. The mid-Holocene footprint of Lake Mina is shown in light gray.

of the soil horizon (d_{soil}). Details of the lumped-parameter, soil-zone model are described in Appendix A4 (see footnote 1). Soil parameters used for the Crow Wing Watershed were adjusted in a model-calibration exercise. The wilting point (expressed in our model in terms of a soil-water height) is defined as the average soil-water depth at which the soil moisture is too low for the plant roots to withdraw water. The soil-water level in excess of field capacity is removed on a monthly basis and serves as infiltration to the aquifer. Soil-zone thickness varied between 2 and 5 m (Lindgren, 2002). Soil-zone parameters used in this model are described in Table 1.

Hydrogeologic Data

As a result of numerous prior hydrogeologic investigations carried out in the Crow Wing Watershed (e.g., Lindholm et al., 1972; Baker et al., 1979; Stark et al., 1994; Winter, 2001; Lindgren, 2002), data on streamflow, groundwater recharge-discharge, stratigraphy, permeability, and other historical data sets (precipitation, temperature, etc.) are readily available. The hydraulic properties of the outwash sands have been measured by >20 aquifer tests. Hydraulic-conductivity values, measured by single- and multiwell aquifer tests performed at the northern edge of the watershed within the outwash sands, ranged from 9.15×10^{-7} to 1.72×10^{-3} m/s^{-1}(Filby et al., 2002).

RESULTS

Model Calibration

The model was calibrated with a 50 yr record (1949–1999) of water-table and lake-level fluctuations and stream discharge measured at Pillager, Minnesota. Hydraulic conductivity and specific yield were varied as part of a model-calibration exercise. The best agreement between simulated and observed water-table elevations was found using the parameters listed in the right column of Table 2. The fluctuations in the computed and observed water-table elevations (Fig. 10) in the uplands (Douglas County wells 1–3) are about the same amount (1–2 m). Computed and observed water levels differ in absolute terms by ~3 m in Figure 10 for wells 1, 2, and 6, whereas for the other wells (3, 4) observed is close to computed. Note that the seasonal water-table fluctuations are generally not available from these wells owing to infrequent sampling. The locations of these wells are shown in Figure 2. The observed and computed water-table fluctuations are of lower amplitude in low land sites (e.g., Cass County wells 4, 5) when compared to upland conditions. This is consistent with simple analytical models for water-table and lake response to climatic fluctuations reported by Urbano et al. (2004).

Computed lake-level fluctuations correspond in general with long-term observed lake-level records at both upland and lowland sites in the watershed (Fig. 11). It should be noted that some lakes (e.g., Lake Ida) were not sampled at a high enough frequency to record seasonal fluctuations during some years. The computed lake levels for the upland lakes seem to fluctuate at the same amount (1–3 m) as compared to the water-table fluctuations at the adjacent wells, which show fluctuations of ~1–2 m (Douglas County wells 1–3). Lake Shamineau, in the central part of the watershed, also showed good agreement with the observed data. Lake Edward, at the discharge area, had higher computed lake-level fluctuations than observed. This could also be attributed to high simulated seasonal stream discharge, which contributed to lake inflows and therefore to the lake-water balance.

Computed monthly stream discharge (1949–1999) at Pillager is also consistent with observed records (Fig. 12) and falls mostly between the ranges of maximum and minimum recorded stream discharges. This model underestimates stream discharges (base flow) for the winter months (November through March), when

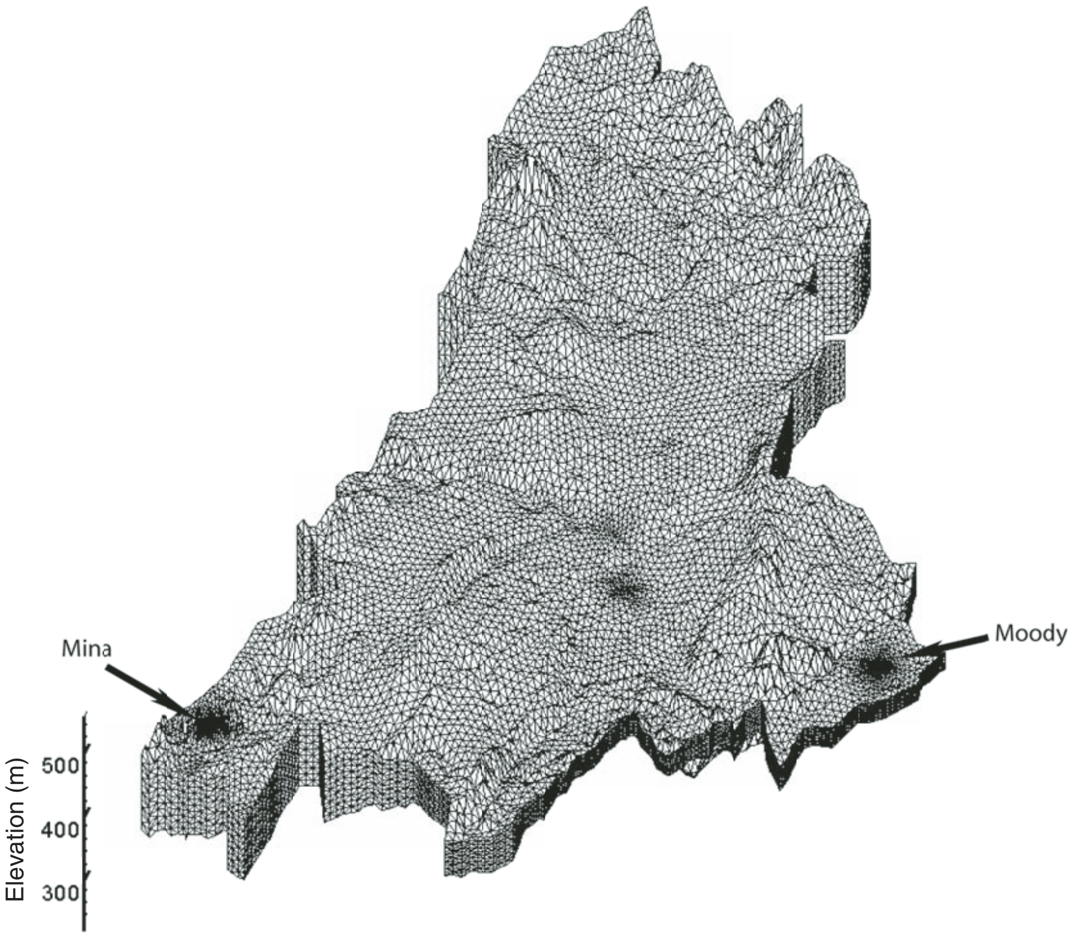

Figure 9. Finite-element mesh of Crow Wing Watershed. Elevation (*z*-axis) is in meters.

TABLE 1. SOIL-ZONE PARAMETERS USED IN CROW WING STUDY

Parameters	Value
Soil depth (d_{soil}, m)	2
Specific yield at field capacity (S_y)	0.27
Field capacity (h_{fc}, m)	0.54
Saturation porosity (ϕ)	0.3
Saturation point (h_f, m)	0.6
Wilting point (h_w, m)	0.47

TABLE 2. COMPARISON OF AQUIFER PARAMETERS FROM MODEL CALIBRATION AND PUBLISHED AQUIFER TESTS

	Hydraulic conductivity K (m/s)	Model (m/s)
Moraines*	0.00002–0.000053	0.00004
Stagnation moraine		0.00007
Ground moraine		0.00011
Outwash	0.00071, 0.0124	0.00071
Specific yield (dimensionless)		
All units*,†	0.1–0.3	0.27

*Lindgren (2002).
†Lindholm (1970).

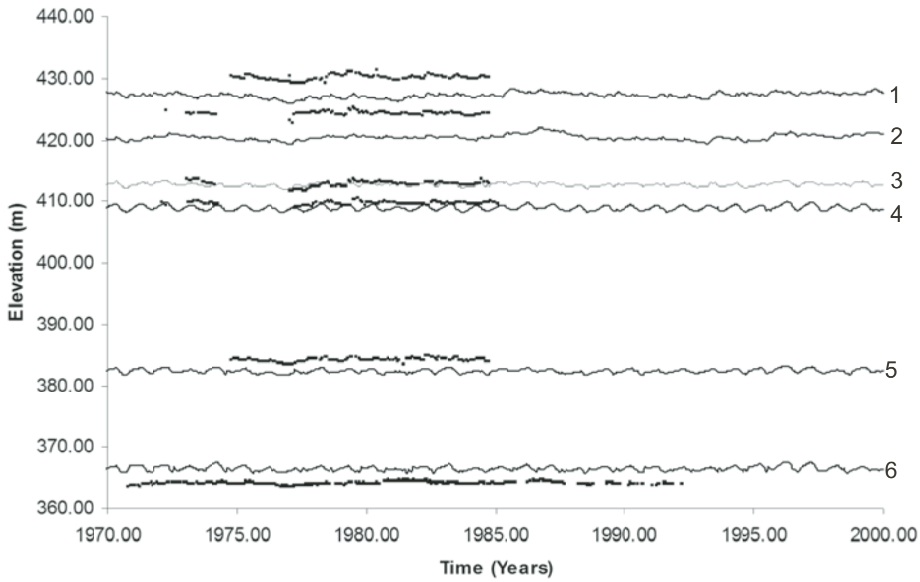

Figure 10. Simulated (line) and observed (squares) water-table elevations at locations 1–3 in Douglas, 4–5 in Cass, and 6 in Crow Wing Counties as depicted in Figure 2.

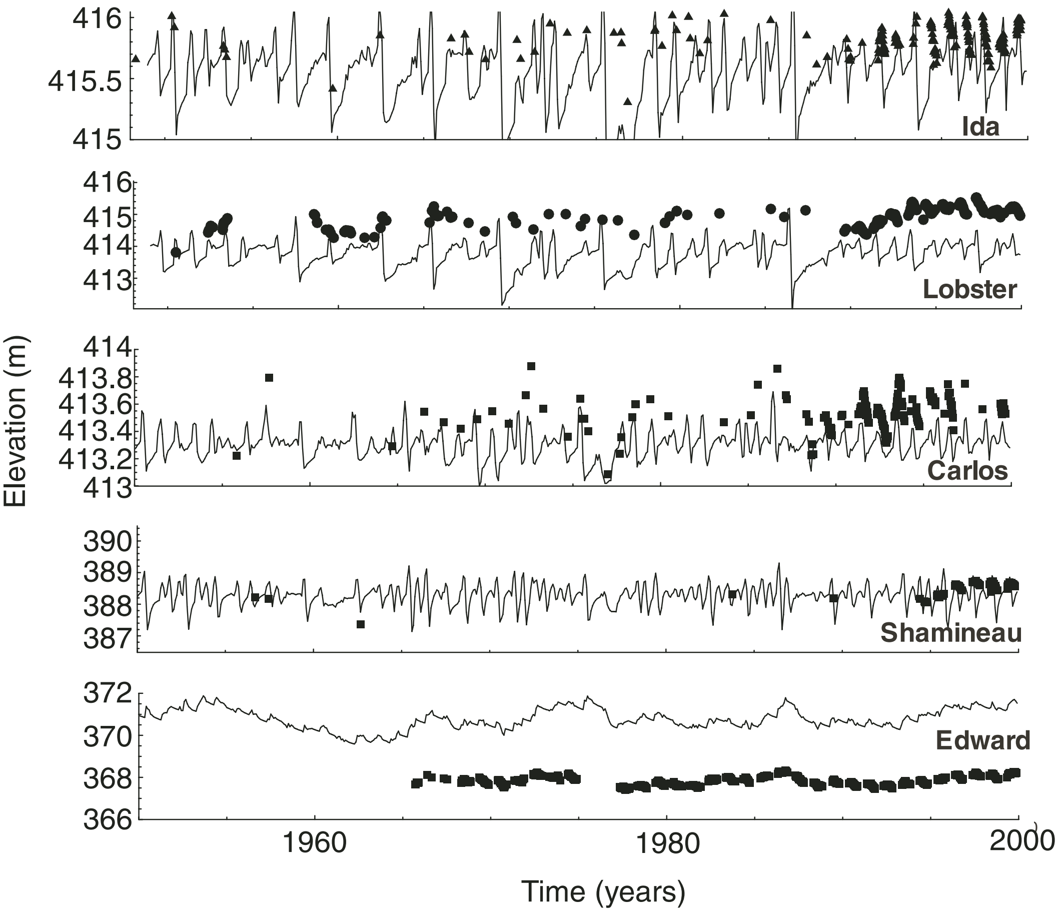

Figure 11. Simulated (lines) and observed (squares, circles, triangles) lake levels. These lakes are shown in Figure 2.

excess precipitation is stored as snowpack. The peak flow in April coincides with snowmelt. The rest of the year (May through October) shows generally good agreement between observed and computed discharge.

Reconstruction of Mid-Holocene Hydrologic Conditions

The calibrated model was next used to reconstruct the mid-Holocene hydrology by increasing the monthly average temperature (and hence, evapotranspiration) and reducing precipitation, consistent with pollen-transfer-function estimates presented in Locke (1995). The calibrated, present-day model was adjusted with the residual method described by Harrison et al. (1998); 25 cm of precipitation was uniformly removed from the monthly precipitation values (~2 cm/mo.), and temperatures were increased by 3.5 °C for winter months and 4 °C for other months (compared to present-day levels). The mid-Holocene simulation was initialized with the modern steady-state, present-day water-table elevation configuration and lake levels. The climate forcing was recycled to extend the 50 yr data set. The simulation was run for 210 yr, by which time lake stages had all stabilized. The model approached dynamic equilibrium conditions after this time (Fig. 13). The levels of lakes close to the watershed boundaries (Lake Mina) declined ~18 m when climatic forcing was applied for the mid-Holocene simulations. It took ~200 yr for lake levels to stabilize for the upland lakes. In contrast, lowland Lake Moody dropped only 8 m and took ~40 yr to stabilize. These drops in lake levels are in relatively good (though not perfect) agreement to the observed drops of 14.7 m and 4.5 m for Lakes Mina and Moody, respectively. The simulated upland lakes had higher-amplitude and lower-frequency fluctuations as compared to the lowland lakes (Urbano et al., 2004; Cohen et al., 2006). It is worth noting that annual peak lake levels in upland lakes show poor correlation with lake-level peaks in lowland lakes, indicating that the response time for the upland and lowland lakes differed (also discussed in Urbano et al., 2004).

During the mid-Holocene the average change in saturated thickness decreased by ~4 m in the outwash sands along the discharge areas to ~17 m over the tills in the upland areas of the Crow Wing Watershed. This represents a decrease of ~3.9×10^{10} cubic meters of storage or ~10% of total storage. Changes in saturated thickness across the watershed are shown in Figure 14. Declines in water-table elevation up to 20 m are greatest for areas of low-permeability tills that also contain a significant number of lakes. The occurrence of lakes in these regions increases surface evapotranspiration, which in turn reduces water-table elevations. Areas containing outwash sands showed lower reductions in saturated thickness. Simulated water-table declines in the Parkers Prairie region studied by Almendinger (1993) had a water-table decline of between 4 and 6 m, consistent with observations (2.8–6.2 m).

Mid-Holocene Surface-Water Hydrology

The mid-Holocene stream discharge for this Midwestern glaciated watershed was significantly different from that of today. The drainage density (Fig. 15) and streamflow (Fig. 16) were reduced substantially during the mid-Holocene. The number of stream segments having a discharge >1 m^3/s was reduced by 67% (Fig. 15). The area of the watershed drained by perennial streams was also substantially reduced. The

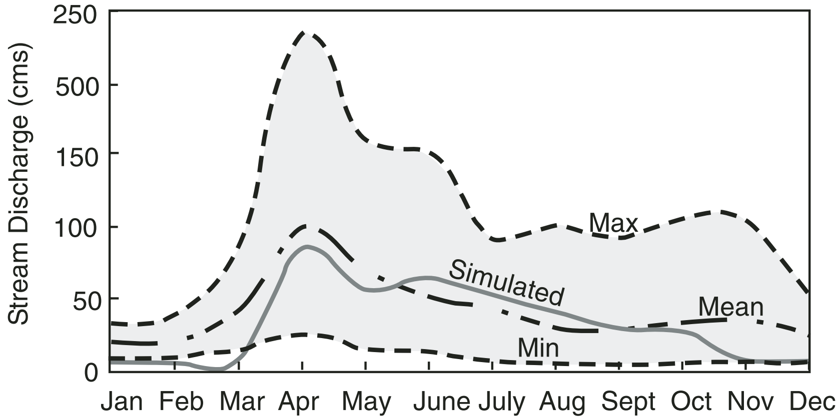

Figure 12. Simulated and observed monthly average streamflow at Pillager. Max—maximum; Min—minimum.

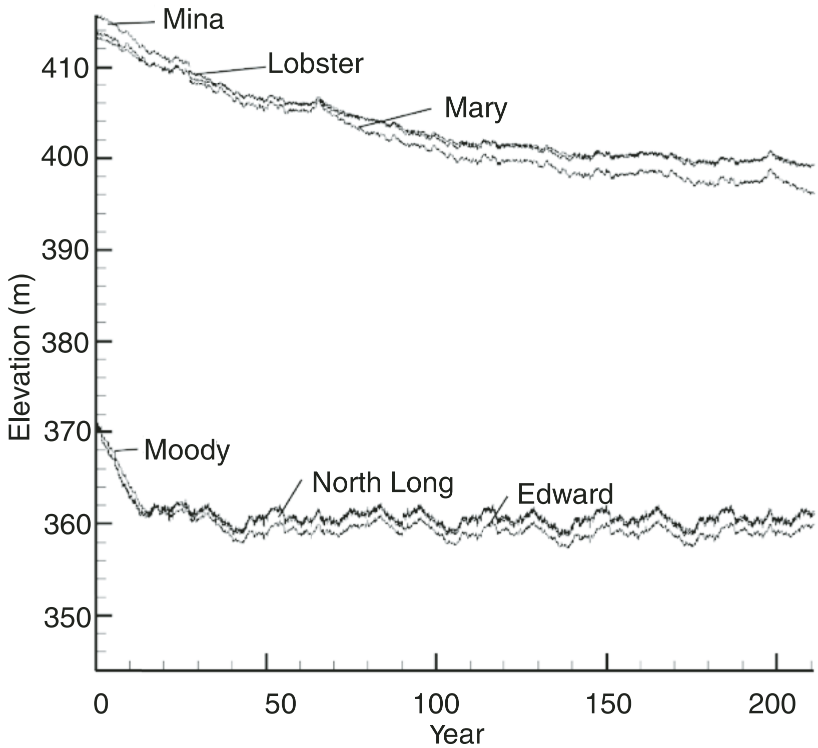

Figure 13. Simulated upland and lowland lake levels during the Holocene. The upland lakes (Mina, Lobster, Mary) dropped by ~8–18 m, whereas the lowland lakes (Moody, North Long, Edward) dropped by only 4–5 m and equilibrated much earlier than the upland lakes.

average soil moisture during the mid-Holocene was reduced by 1.7 cm.

The total annual discharge of the watershed at Pillager was reduced by 70.5% of the modern annual discharge (387 m^3/s). Temporal trends in average monthly streamflow were also different during the mid-Holocene (Fig. 16). Increased temperatures resulted in a reduction in water storage as snow in winter. The discharge reached its peak in the month of April and then remained more or less steady for the rest of the year. The stream discharge fluctuated less than under present conditions. This more uniform trend in runoff is more typical of states farther south within the Mississippi River Watershed such as Missouri (Pitlick, 1997).

The average annual computed spring recharge for the mid-Holocene was reduced from 3.75 to 2.04 cm for the months of March through May. There was 38.6% less groundwater recharge during the mid-Holocene than at present (9.5 cm/yr). Evapotranspiration accounted for 85% of total precipitation (43.2 cm/yr) in the mid-Holocene in comparison with 67.7% of total precipitation (67.15 cm/yr) at present. Evaporation from lakes (150% of precipitation) was significantly higher during the mid-Holocene when compared to modern levels calculated by our model (77%). The difference in the rate of evapotranspiration in soils relative to lakes is due to soil-moisture levels that fall below the wilting point. Wetland areas were also reduced in area by 16.9% in the mid-Holocene in comparison with the present. Today, wetlands occupy ~5.6% of the watershed.

DISCUSSION

The position of mid-Holocene lake levels, indicated by the location of beach sand buried in lake sediments, is in relatively good agreement with simulated lake levels of that period. This study, along with those by Almendinger (1993), Filby et al. (2002), Smith et al. (2002), and Donovan et al. (2002), demonstrates that interpretations of the effect of climatic change on lake levels need to consider groundwater hydrodynamics and analysis of the relative positions of the lakes within watersheds as well as local permeability. Lakes hosted in relatively low-permeability tills in our model underwent larger lake-stage changes during the mid-Holocene than did those lakes situated in relatively sandy deposits. The issues of lake position within the watershed and permeability conditions preclude making many generalizations regarding an individual lake's response to climate change. However, reproducing lake-level fluctuations using historical records helps build confidence that "hindcasts" have some measure of credibility, especially when paleolake levels are available from some lakes within the watershed. It is worth noting that our findings are also consistent with ecological studies that showed a close correlation between lake chemistry and lake position within the watershed (Webster et al., 1996; Soranno et al., 1999). These studies found that lake chemistry changes in response to drought conditions and varies with position within the watershed. This is consistent with the integrating effect of aquifer systems to chemical contributions (Kirchner et al., 2000).

During the mid-Holocene, the river-drainage networks changed substantially in response to increased evapotranspiration and a lower water table (Fig. 15). For example, the northernmost section of the Crow Wing River (Fig. 3; labeled 1 in Fig. 15A), which currently flows

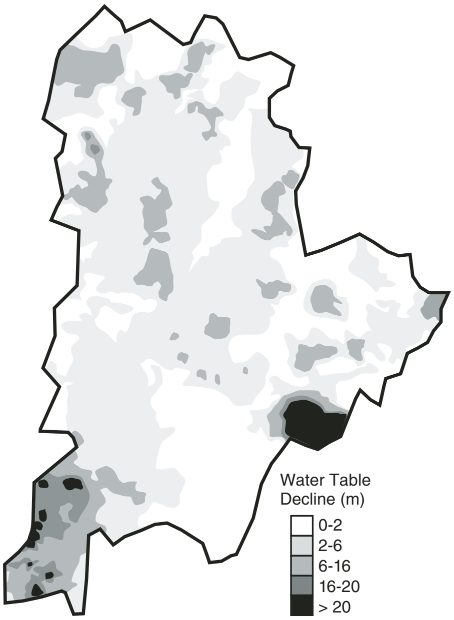

Figure 14. Computed changes in saturated thickness (in meters) across the Crow Wing Watershed between the mid-Holocene and present.

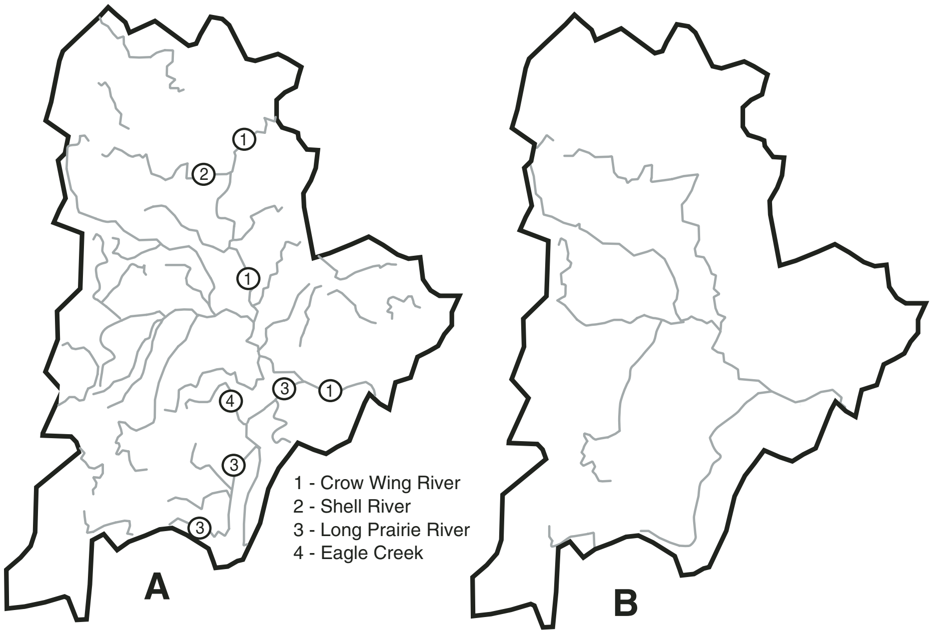

Figure 15. Comparison between modern (A) and mid-Holocene (B) stream networks. Stream segments represented have discharge greater than 1 m³/s. Labeled streams are discussed in the text.

through the chain of Crow Wing lakes, dries up (Fig. 15B), and the headwaters of the Crow Wing shifts to the Shell River (labeled 2 in Fig. 15A). It is likely that Shell River is maintained because of the vast amount of outwash in the area around Park Rapids in the northwestern part of the watershed. In the southern part of the Crow Wing Watershed many tributaries to Long Prairie River (labeled 3 in Fig. 15A), such as Eagle Creek (labeled 4 in Fig. 15A), dry up as well. Straight River (Fig. 3), a tributary to Shell River (not shown in Fig. 15A), just to the north of Shell River, is a critical stream for trout habitat (e.g., Stark et al., 1994). Changes to the stream network, as well as changes in stream discharge, might have affected aquatic biodiversity. Our findings are consistent with Holocene paleoflood chronologies from the Upper Mississippi Valley Watershed (Knox, 2000).

Although our model provides a spatially, relatively high-resolution picture of watershed hydrologic conditions when compared to a land-surface grid of a global climate model (GCM), it is still relatively coarse and does not account for hydrologic processes such as unsaturated flow. In the vicinity of the Crow Wing lake chain in the northern section of the watershed (Fig. 2), our model predicted relatively modest water-level declines (0–2 m) during the mid-Holocene. However, some lakes have undergone much larger lake-stage changes during the last century. Lake Belle Taine, for example, has fluctuated over a 4-m range since 1935 (http://www.dnr.state.mn.us/lakefind/index.html; Fig. 2). In the case of Belle Taine, and several other lakes in the Crow Wing Watershed in a similar geologic setting, lake-stage fluctuation is enhanced because the lake receives surface-water flow but has no surface-water outlet. During wet periods the additional gain from surface-water inflow is only partially offset by a slower loss of lake water to groundwater, which causes the lake stage to rise more than most other area lakes (Rosenberry, 2000). In addition, the model also predicts large head declines (~20 m) in the southeastern part of the watershed (Fig. 17). This may be due partly to the coarse spatial grid discretization and the presence of a number of very large lakes (Fish Trap Lake, Lake Alexander, Shamineau Lake; see Fig. 2). Our model predicted lower potential evapotranspiration

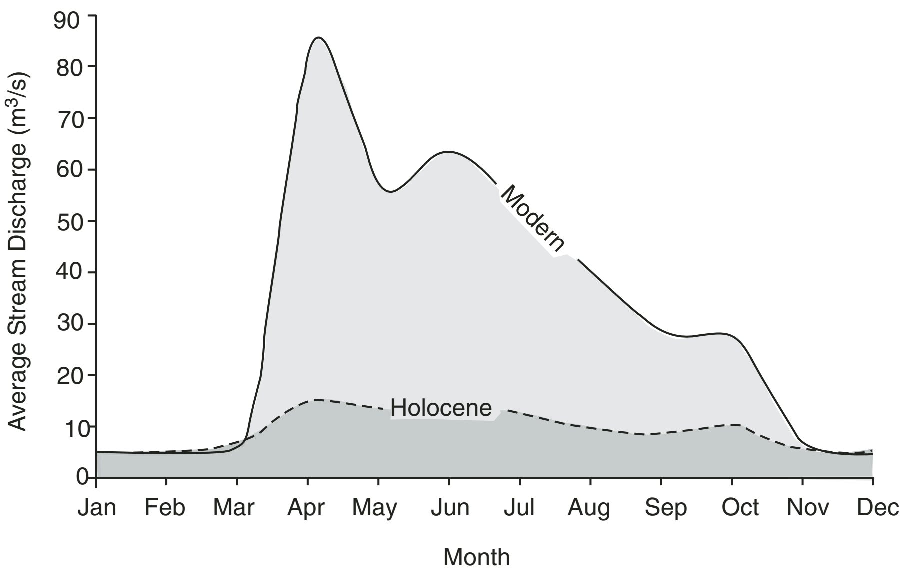

Figure 16. Comparison of mid-Holocene and modern simulated average monthly streamflow at Pillager.

levels (77% of local precipitation) when compared to actual measurements made at one lake at the northeastern edge of the watershed (100% of precipitation; Hostetler, 1997; Stannard et al., 1997). It is not clear whether the observed measurements are representative of conditions over the entire watershed. Finally, our model predicted about twice the magnitude of lowland Holocene lake-level change than was observed in Moody Lake (predicted, 8 m; observed, 4.5 m). Given the spatial extent and complexity of our model on the one hand, and the simplifying assumptions (e.g., aquifer heterogeneity, calculated monthly evapotranspiration) required to represent watershed hydrology on the other, we do not find such discrepancies surprising or unexpected. However, we think that the patterns of change (i.e., greater lake and water-table declines in the uplands, and less in the lowlands) are accurate.

Projected future changes in climate for the central United States provide some context for the paleoclimate differences from the present climate predicted by our models. Projected changes depend on gas- and aerosol-emission scenarios and simulation models, but they show a broadly consistent picture. Under the Special Report on Emissions Scenarios (SRES; Cubasch et al., 2001) for the A2 and B2 scenarios, annual temperatures for the last 30 yr of the twenty-first century are estimated at approximately 4 °C higher than at present, though there is a comparable spread among the GCMs used to make the projections (Cubash et al., 2001). Variations in projected temperatures for the Midwestern United States are illustrated by the work of Giorgi and Francisco (2000). In contrast to GCM mid-Holocene climatic reconstructions (e.g., in COHMAP, 1988, 6 ka summer and winter temperatures were not significantly different from modern levels), projected winter (December through February) and summer (June through August) temperatures for the end of the twenty-first century (e.g., Fig. 17) show warming in both seasons, despite a substantial spread among the models analyzed (Giorgi and Francisco, 2000).

Projected changes in precipitation show mixed results. The annual precipitation for the last 30 yr of the twenty-first century under SRES A2 and B2 scenarios shows relatively little change for central North America, with the northern part of the region tending toward a few percent increase and the southern part toward a few percent decrease (Cubasch et al., 2001). Winter and summer changes (e.g., Fig. 17B) suggest a small winter increase and a summer decrease (Giorgi and Francisco, 2000). Although the spread among models includes both increases and decreases in precipitation, a significant decline in precipitation is predicted in some models for central North America, not unlike pollen-based climate reconstructions from the mid-Holocene. Thus, the model reconstructions presented here probably represent a worst-case scenario of a dry future climate for Minnesota.

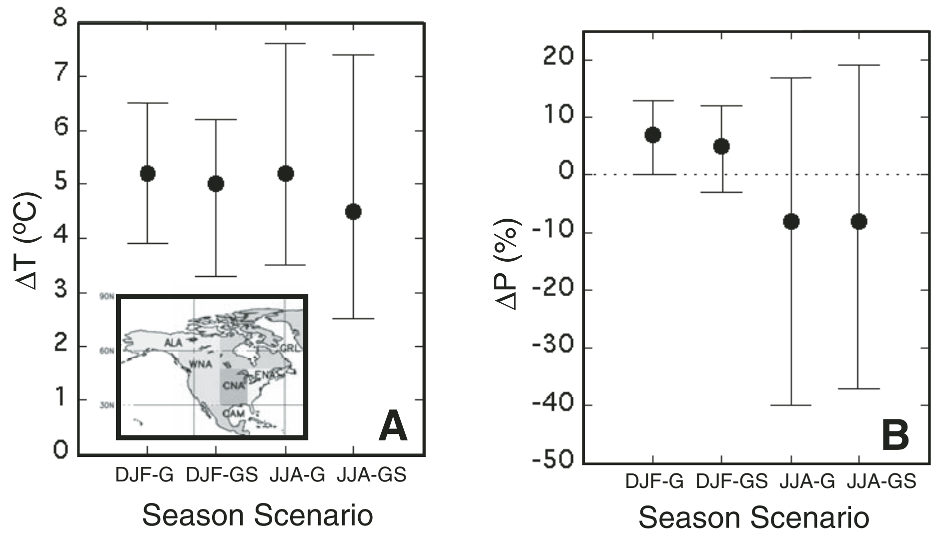

Figure 17. Changes (2071–2100 minus 1961–1990) for central U.S. temperature (A) and precipitation (B) among global climate models (GCMs), using a 1% annual compounded increase in CO_2 with (GS) or without (G) sulfate aerosol effects (adapted from Giorgi and Francisco, 2000). Solid circles are averages over the GCM ensemble; I-bars mark the extremes. Computed summer and winter changes in climate are denoted by JJA (June, July, August) and DJF (December, January, February), respectively. ΔT—changes in temperature (°C); ΔP—percent change in precipitation.

SUMMARY AND CONCLUSIONS

The focus of this study was to assess the effects of past climate change on groundwater and surface-water resources across a large glaciated watershed in Minnesota through a combination of field-data collection and mathematical modeling. Lake and adjacent water-table levels at Lake Mina and Moody Lake, at opposite ends of the Crow Wing Watershed, were monitored for 2 yr, and we found a close correspondence between lake and water-table fluctuations. Analysis of historical lake-level records from 28 lakes and 5 wells suggests that water levels in the lowest parts of the watershed fluctuated less than those of upland lakes under the same short-term climate forcing. The upland lakes responded with higher-amplitude and lower-frequency(?) fluctuations to periodic climatic forcing than lakes near the outflow point of a watershed. Maximum lake-level and water-table fluctuations during the past 50 yr were ~2 m. Moody Lake and Lake Mina sediments were cored to determine hydrologic response of the watershed to the Mid-Holocene Warm Period. Lake-sediment records indicate that the level of Lake Mina declined ~15 m and the level of Lake Moody declined ~4.5 m in response to mid-Holocene climatic change. Results from numerical modeling indicate that the stage of Lake Moody started to decline at a higher rate with the onset of mid-Holocene climatic forcing (first 10 yr) but then gradually attained a steady-state condition within ~40 yr. Lake Mina declined steadily at a relatively lower rate for the initial 100 yr and then took ~200 yr more to attain a steady state. The longer duration for Lake Mina to stabilize is partly attributed to the fact that it lies in poorly permeable moraines. The simulated surface-water network, having a discharge of at least 1 m^3/s, decreased by 67%. Wetland areas were reduced by ~17%. Soil-moisture levels decreased by 1.7 cm during the mid-Holocene. The findings of this study support the hypothesis that lakes within different parts of a watershed respond differently to the same climatic forcing. This study found that substantial changes in the watershed hydrology occurred during the mid-Holocene, including substantial declines in streamflow, perennial-stream network, and water storage. These findings give insights into possible future hydrologic conditions as suggested by some low precipitation AGCM model forecasts for central North America.

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